TACTICAL DATA LINKS, AIR TRAFFIC MANAGEMENT, AND SOFTWARE PROGRAMMABLE RADIOS*

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Abstract

Background on Link 16, global air traffic management (GATM), and the joint tactical radio system (JTRS) is provided. Information addressing the ability of: 1) Link 16 to handle evolving civil aviation data link (CADL) waveforms; 2) a single data link to satisfy Air Force GATM requirements; and 3) JTRS to incorporate data links of interest to aviation is offered. Relationships with layered communication architectures, the Global Grid, and software programmable radios (SPRs) are also discussed.

1. Introduction

In October 1994 Link 16 was designated as the DOD's primary tactical data link for all military service and defense agency command, control and intelligence (C^2I) systems [1]. The Air Combat Command (ACC) has already incorporated Link 16 into its C^2 and sensor systems and is now planning on installing Link-16 in its fighters and bombers. This commitment entails an expenditure of billions of dollars.

However, there are other data link requirements competing for DOD resources, notably those of the International Civil Aviation Organization (ICAO) for communications, navigation and surveillance/ air traffic management (CNS/ATM). In 1997 the Air Force created a global air traffic management (GATM) function in a new system program office (SPO) at Hanscom Air Force Base (AFB) to include the certification of avionics capabilities from a GATM perspective. A question asked by the commander of the Aerospace C^2 Intelligence, Surveillance, and Reconnaissance Center (AC^2ISRC) was: Why can't civil aviation data link (CADL) requirements be satisfied by Link 16? Another question is whether a single CADL can satisfy Air Force GATM needs.

An objective of this paper is to answer these questions. Section 2 briefly introduces the Link 16 program. CADLs and implications for DOD are discussed in Section 3. Section 4 highlights difficulties of integrating Link 16 and CADLs waveforms, and relying on a single data link to satisfy CNS/ATM data link requirements. Section 5 discusses SPRs and the JTRS. Section 6 has concluding remarks and suggested actions.

2. Link 16

Link 16 is NATO terminology for an anti-jam (AJ), secure, data and voice system, with standard waveforms and messages to promote interoperability, supported by the Joint Tactical Information Distribution System (JTIDS) and Multifunctional Information Distribution System (MIDS) terminals.

Figure 1 shows how the number of platforms to receive Link 16 rapidly rises starting in FY00, and the significant changes in the increases from FY03 through FY15, based on various planning data [2].

3. Civil Aviation Data Links

CADLs are primarily associated with ATM systems, and include fixed message sets built into upgraded but standard communication procedures to reduce pilot and controller workload and lead to quieter cockpits and airwaves. Also, CADLs on military aircraft could be used as a resource for C^2. ICAO's CNS/ATM concept relies on data links to be the primary means of routine

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communications for air traffic services (ATS) [3]. Controller-pilot data link communications (CPDLC) is the first comprehensive ATS data link application to be implemented.

Line of Sight (LOS) Data Links

The FAA is advocating a new digital voice and data time division multiple access (TDMA) waveform for their next-generation air-ground communications (NEXCOM) system. This waveform is known as Mode 3 of the VHF digital link (VDL-3). In 1995 ICAO endorsed VDL-3 as the long-term solution to worldwide spectrum congestion in the VHF aeronautical band. VDL-3 operates at a 25-kHz channel data rate of 31.5 kb/s. The VDL-3 end-to-end delay is no more than about 250 ms, a latency suitable for ATS.

Another future CADL, VDL-2, uses the same modulation scheme as VDL-3 but employs carrier sense multiple access (CSMA) instead of TDMA. VDL-2 is attractive to airlines for aeronautical operational control (AOC) where latency requirements for data are not so stringent, as compared to ATS.

Any of the time-critical functions of CPDLC are more in the bailiwick of ATS, not AOC, and at VHF should be handled by VDL-3, not VDL-2. However, VDL-2 could be around for a long time, and additional ATS uses for VDL-2 that do not require near-real-time latency performance could be attractive.

Automatic dependent surveillance broadcast (ADS-B), a CADL system critical to "free flight", is devoted to the LOS broadcast of position, velocity, and intent information. Potential solutions to ADS-B are the Extended Squitter, Self-Organizing TDMA (S-TDMA) (also known as VDL-4), and the Universal Access Transceiver (UAT).

Beyond Line of Sight (BLOS) Data Links

Inmarsat aeronautical (Aero) satellite communications (SATCOM) is certifiable for BLOS air traffic control (ATC) use. ICAO does not yet require dual redundant satellite communication systems for ATC but probably will. Many potential users, particularly the airlines, have advocated HF data link (HFDL) for over the ocean ATC instead of a second satellite system because HFDL is less expensive to install. The author expects a SATCOM/HFDL configuration to become acceptable for ATC after some further FAA effort to validate HFDL for this application.

It is noted that Inmarsat's geostationary satellites do not provide polar coverage, a desirable feature for military applications. However, the narrowband ICO system will provide global coverage. Although there has been interest in providing aeronautical service with ICO, this capability is not yet realized. HFDL may also support global coverage.

Implications for DOD

DOD must comply with civil standards being developed by ICAO. With the assistance of Hanscom's GATM SPO, the Air Mobility Command (AMC) is planning to integrate ADS-A, Aero-I, and HFDL, into its operational airlift capabilities.

ACC has been concerned about equipping all their aircraft with avionics equipment that would make them compliant with the emerging civil aviation standards. The "heavy special use aircraft" that routinely fly as general aviation traffic (GAT) aircraft, viz., the E-3 (Airborne Warning and Control System [AWACS]), E-4 (command post aircraft), E-8 (Joint Surveillance Target Attack Radar System [JSTARS]), and the OC/RC/TC-135 (reconnaissance and tanker aircraft) would be fully equipped. However, it was questionable whether it would be necessary to equip fighters, bombers, and EC/HC-130s (transport aircraft).

Overall, considerable progress has been made in the last two years. The number of GATM communications (comm) functional units planned for various aircraft between 1999 and 2016 are shown in Figure 2. CMU stands for communications management unit.

4. Integration of Link 16 and CADLs

Section 1 questions are now addressed.

Layered Communication Architecture

A "layered" communication system architecture is advocated as a tool for analyzing the integration problem. Ideas of a MITRE colleague, Mike Butler, are freely used. He has elaborated on several key attributes of layered architectures: 1) technology neutrality; 2) functional encapsulation; 3) interface standardization; 4) independent resources; and 5) extensible systems. Layering facilitates performance vs. flexibility tradeoffs as technology and system needs change. This helps ensure the architecture accommodates system evolution over a long period.

An example of a general, layered communication architecture is the 7-layer model of the International Standards Organization (ISO). This model is well known and has been applied successfully.

A tenet of layering is to partition the implementation of functions so that each self-contained physical entity within a system realizes only functions within the same layer of the architecture. An example is when a radio contains only the hardware and software necessary for performing modulation/ demodulation and coding/decoding associated with the physical layer and data link layer, respectively, of the OSI model. The JTIDS/MIDS radios (which are contained in the terminals) already follow that precept in part.

However, in general, the Link 16 system does not have a full layered architecture because the tenet of layering stated above is not always followed. First, portions of the network and cryptographic management functions reside within the message signal processor of the “radio”. The rest of these two functions reside in the network interface computer of the terminal outside the radio. Furthermore, not everything required by the Link 16 system resides in the JTIDS/MIDS terminal. A given Link 16 platform's host computer contains the required databases, various controls, message processing, interface, input/output, and other functions. Thus, if a hardware or software change outside the terminal becomes necessary, all the host platforms must be modified.

Although layering implies modularity, the reverse is not necessarily true. However, two or more adjacent layers can be combined in some situations to save space. One just has to be careful that when layers are combined, future flexibility is not precluded.

Contrasts Among Link 16 and CADL Waveforms

As an exercise in preparing this paper, the author allocated some basic functions of Link 16 and VDL-3 to the ISO layers. In doing this, it became apparent that Link 16 and CADLs of interest have many fundamental differences. Link 16 employs an L-Band, 3 MHz-bandwidth, fast-frequency-hopping, AJ-coded, multi-pulse waveform with encrypted messages. VDL-3 is a VHF, 25 kHz-channel, non-hopping, non-AJ, multi-mode, waveform with un-encrypted messages. The time slot and coding structures of the two schemes are very different. Furthermore, the ground infrastructure for interconnecting the two systems does not exist. This does not bode well if Link 16 is to accomplish all the functionality of the CADLs becoming required by the FAA and civil aviation authorities (CAAs). There are too many practical hurdles to overcome that hinder the cost-effective integration of these waveforms. This answers the first question of Section 1.

A Potentially Attractive Approach to Accommodating Link 16 and CADLs

Instead of attempting to have Link 16 accommodate CADL waveforms, a better approach may arise from asking: What can be done to protect the investment in Link 16

radios while providing a more affordable way of handling CADLs?

First the military's "Global Grid" is mentioned as being relevant to the architectural discussion. The Global Grid vision – any user communicating with any other user – is derived from DOD's Joint Vision 2010. Because of the increasing demand for more bandwidth to accommodate higher data rates, the means for attaining this goal is based primarily on wideband capabilities promised by SATCOM, microwave, and fiber optic communications media.

It is important to distinguish what is – from what is not – part of the Global Grid. The Global Grid encompasses only the bottom four layers, the physical, link, network, and transport layers of the OSI model. The session, presentation, and application layers are on the users' side of the architecture. The Global Grid "merely" transports already-composed messages as reliably and speedily as possible. If done thoroughly the functions of Link 16 will probably map to all levels of a layered architecture, and therefore from the outset, Link 16 is not compatible with the Global Grid bottom-four-layers concept.

What about isolating the radio functions from the application functions in both the Link-16 system and the CADLs? In this approach the data link "essence" of Link 16 and the CADLs would not have anything to do with the networking (or above) layer(s). One would have "plug-in" "Link-16 " and "CADL" PC-like cards that could provide the physical and data link layer functions. All upper-layer functions would be provided by a standard protocol stack.

If only the true physical and data link layer functions resided in the JTIDS/MIDS radios, it may be possible to build them smaller and cheaper; and similarly for CADL radios. Also, one might be able to choose the messages and the media independently making possible the passing of Link 16 messages over CADL radios, and aeronautical messages over Link 16 radios. An aircraft platform might be configured more easily to suit particular missions.

However, the author adds some words of caution: Before abandoning the present system configurations, the possibilities promised by this approach should be explored in detail to be assured that all essential system functions are preserved and acceptable performance requirements are met.

One way of thinking about this problem is depicted in Figure 3. Each "slice" represents a distinct viewpoint within the ISO-model layer, data link system, or performance/ flexibility parameter plane. Just a few systems and parameters are illustrated; there may be many more of importance. Within each parameter there can be various aspects corresponding to different layers of the model. Several of these are shown for vulnerability and latency.

One idea concerning Figure 3 is as follows. The goal of integrating different data links from the point of view of the layered model may be facilitated by "scrubbing" performance-flexibility tradeoffs among systems. The benefit of greater flexibility in applying commercial standards and technology may be worth giving up some performance.

Comparisons/Contrasts Among Civil Aviation Data Links

Now the second question, whether the Air Force should employ only one CADL is considered. Various CADLs have distinctive characteristics. Important features and limitations of Aero C, H, I, and L data links, HFDL, VDL- 2, 3, and 4, UAT, Extended Squitter, and Mode S data link are summarized in Table 1.

Essential characteristics of these CADLs are arranged in Table 1 with respect to attributes of considerable interest for civil aviation communications. Some attributes relate to the application being addressed; others

refer to desired performance within a given application; and others refer to schedule and/or costs associated with implementation. In the interest of brevity this table is primarily qualitative. The value judgments indicated by the "colors" are the sole responsibility of the author.

Based on material developed for Section 3 and the entries of Table 1, the author concludes that the Air Force cannot expect to satisfy all its CADL needs with a single CADL. Every CADL has at least one "red" (R) entry in a critical row. For example, in just considering ATS and ADS-B, applications necessary for flying in terminal airspace and free flight, respectively, no CADL can readily accomplish both functions.

Given this conclusion, what should the Air Force do? The author recommends that the Air Force plan to acquire VDL-2 radios that have the assured capability of being upgraded to VDL-3. Several vendors have developed suitable VDL-2 radios, and prototype VDL-3 radios have been successfully demonstrated. If VDL-3 does not materialize by 2007, as expected, at least the Air Force would have a good CADL capability for C^2 operations, albeit, VDL-2 is non-real-time and not appropriate for time-critical ATS messages. Regarding ADS-B, the author recommends the Air Force analyze the results of last summer's Safe Flight 21 tests and plan for the best single ADS-B data link implementation.

Also, the Air Force might benefit by continuing to plan for HFDL and Aero-I, and waiting a little longer before reassessing and deciding whether any of the emerging commercial satellite systems would provide adequate alternative data link capability.

5. Software Programmable Radios

Commercial radio technology has progressed to where more waveform processing functions can be accomplished with software instead of hardware; greater flexibility and cost effectiveness might be achieved.

This has led to the concept of SPRs or software defined radios (SDRs) [5]. In turn this has spawned a joint service program for acquiring future radios with a new evolutionary, open-system, JTRS architecture.

One of the first examples of a military SPR was SPEAKeasy, a prototype development conducted jointly by the Army and Air Force, and later under the auspices of DARPA. Another such effort is the Air Force's Airborne Information Terminal (AIT). The Army and Navy also have other candidate radio programs heading in this direction.

The JTRS modes and capabilities are based on the JTRS operational requirements document (ORD) [6] for handheld, dismounted, vehicular, maritime/fixed, and airborne operational domains.

The author notes that radio capabilities for ATC, i.e., HFDL, 8.33 kHz, and the VDL are included. HFDL and VDL are not required for the JTRS until FY03. Also, there is some concern in noting that SATURN, the NATO version of the fast-frequency-hopping upgrade to Have Quick II, is scheduled for airborne operations as late as FY04. One would hope that SATURN would be implemented earlier to better test the capabilities of the JTRS architecture. It is also noted that UHF DAMA, and other AIT capabilities are included in the ORD. Several L-Band waveforms are included, notably, Link 16 and Mode S Level 4, but there is no mention of the Extended Squitter, the UAT, or S-TDMA.

The author wonders whether too many JTRS waveforms are being contemplated. A late 1998 Defense Science Board (DSB) recommendation suggested that the JTRS program concentrate on new data link and networking capabilities, and implement only a small subset of the waveforms in the ORD.

Because Link 16 has been selected as the tactical C^2 data link of choice for all of DOD, and is being implemented on thousands of Air Force platforms, this system will be around for a long time. Therefore, a Link 16 capable waveform should be included in the JTRS. According to the JTRS implementation plan, Link 16 is to be realized within a JTRS SPR by FY03. The author thinks this is good but would like to see Link 16 accommodated sooner.

6. Conclusions

The Link 16 system cannot satisfy the emerging CADL requirements in a cost-effective manner.

No single data link will satisfy the Air Force's CADL needs.

Although none of the CADLs are required before 2003, VDL-2 will likely be implemented before then. VDL-3 is to be implemented starting in 2007. A CADL for ADS-B may be implemented sooner than expected. The Air Force should acquire VDL-2 radios that have the assured capability of being upgraded to VDL-3, plan for ADS-B, and continue to follow but await further commercial SATCOM developments.

There is high-level commitment to Link 16 as the tactical data link of choice for DOD C^2I systems. Large expenditures of U.S. taxpayer dollars are planned for the phased implementation of this system on-board thousands of aircraft critical to the national defense and warfighting capability of the U.S. Hence, Link 16 should be accommodated by the Global Grid and JTRS programs.

The JTRS program should emphasize Link 16, arguably the most challenging and most important wideband waveform of the foreseeable future. One suggestion might be to include a task for detailing the relationship between Link 16 and the OSI model as part of both the Link 16 and JTRS technological roadmap efforts.

Contributors and decision-makers should work on the concept of relaxing requirements and increasing architectural flexibility where possible.

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[6] 23 March 1998, Operational Requirements Document (ORD) for Joint Tactical Radio (JTR)

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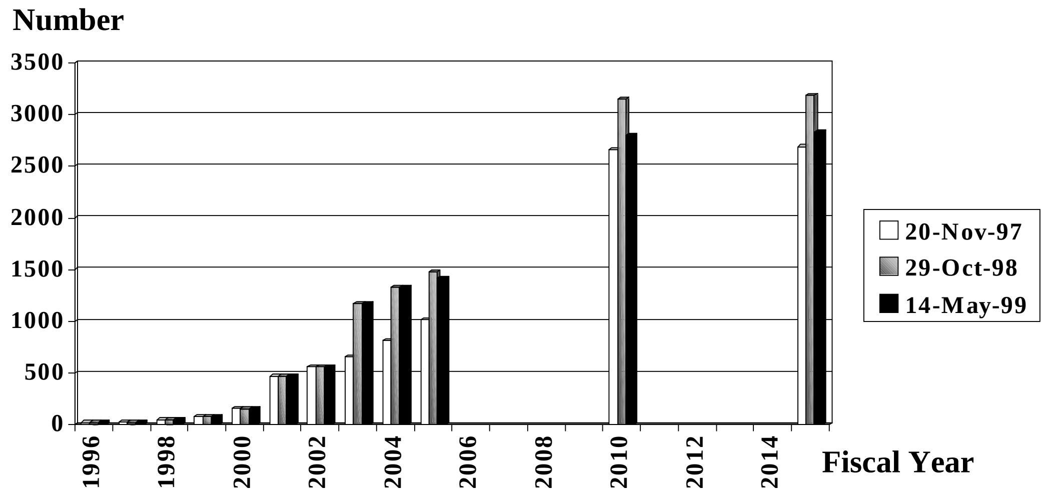

Figure 1. Number of Air Force Data Link Platforms Programmed for Link 16

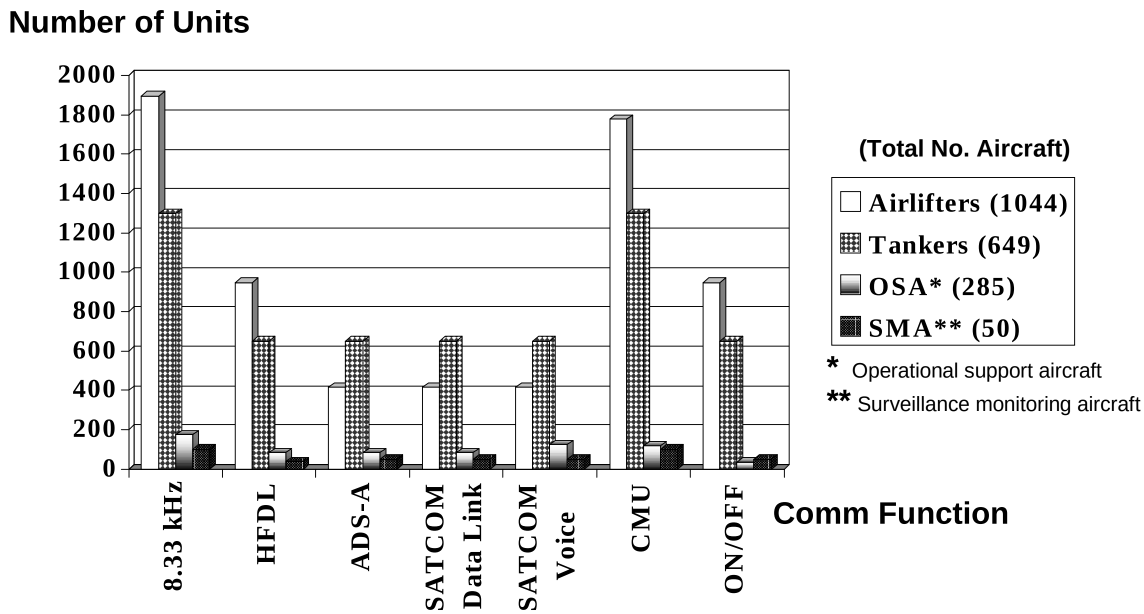

Figure 2. Planned Communications Functions for Various Air Force Platforms (Through 2016)

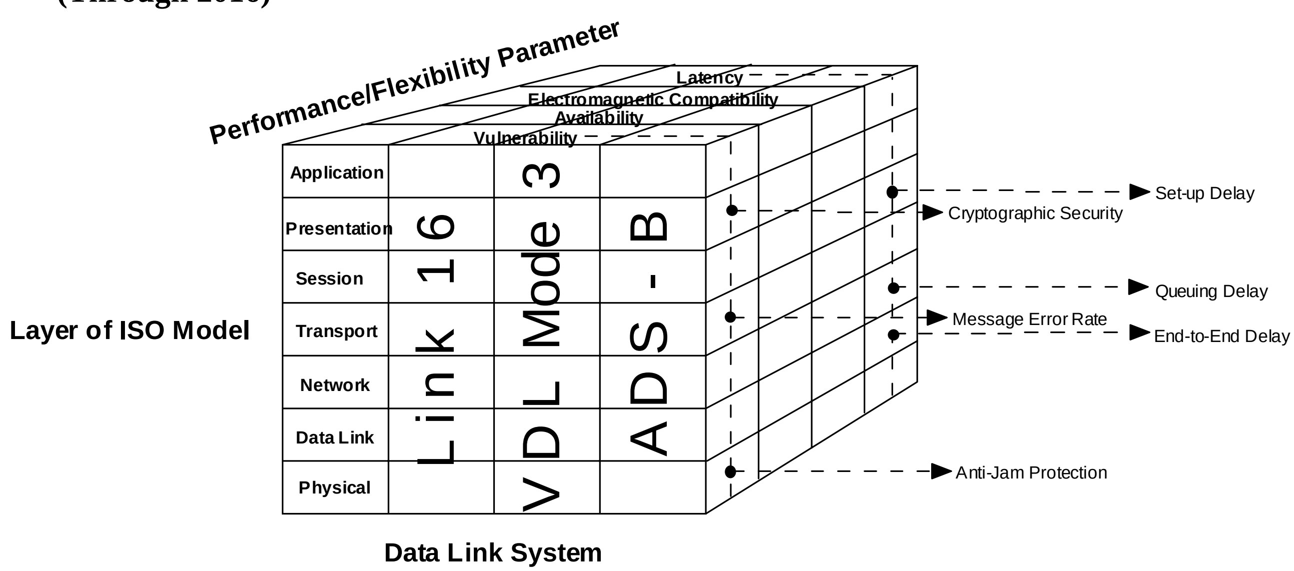

Figure 3. One View of Integrated Data Link Solution Space

Table 1. Civil Aviation Data Link Characteristics

	Civil Aviation Data Link										
Application, Performance, or Schedule/Cost Attribute	**Aero C**	**Aero H**	**Aero I**	**Aero L**	**HFDL**	**VDL – 2**	**VDL – 3**	**VDL – 4**	**UAT**	**Extended Squitter**	**Mode S**
Primary Operational Areas	Oceanic Over Land – B	Oceanic Over Land – B	Oceanic Over Land – B	Oceanic Over Land – B	Oceanic Over Land – B	Over Land: Ground sites – Y	Over Land: Ground sites – Y	Over Land Oceanic – B	Over Land Oceanic – B	Over Land Oceanic – B	Over Land: Ground sites – Y
Coverage	BLOS: $\leq 70^{o}$ N/S latitude – Y	BLOS: $\leq 70^{o}$ N/S latitude – Y	BLOS: $\leq 70^{o}$ N/S latitude – Y	BLOS: $\leq 70^{o}$ N/S latitude – Y	BLOS: Propagation anomalies – G	LOS – G	LOS – G	LOS – G	LOS – G	LOS – G	LOS: $\geq$ 15 kft – Y
Terrestrial Design Range (based on link budgets)	Long – B	Long – B	Long – B	Long – B	Long – B	200 nmi – G	200 nmi – G	No info – G	100 nmi – Y	100 nmi – Y	100 nmi – Y
ATS	No – R	Yes – G	Yes – G	Yes – G	Possibly – Y	Only for Non-Time Critical –Y	Yes – G	No – R	No – R	No – R	No – R
AOC	No – R	Possibly – Y	Possibly – Y	Possibly – Y	Possibly – Y	Yes – G	Yes – G	No – R	No – R	No – R	No – R
ADS-A (two way)	No – R	Yes – G	Yes – G	Yes – G	Yes – G	Yes – G	Yes – G	No – R	No – R	No – R	Possibly – Y
ADS-B (one way)	No – R	No – R	No – R	No – R	No – R	No – R	No – R	Yes – G	Yes – G	Yes – G	No – R
Frequency Band (color indicates propagation effects, e.g., external noise, multipath, etc.)	L-Band – G	L-Band – G	L-Band – G	L-Band – G	HF: 3–30 MHz – R	VHF: 118–137 MHz – Y	VHF: 118–137 MHz – Y	VHF: 120–150 MHz [4, p. 52] – Y	L-Band: 966 MHz (could move) – G	L-Band: 1030 MHz up; 1090 MHz down – G	L-Band: 1030 MHz up; 1090 MHz down – G
Channel Bandwidth	5–10 kHz – R	5–10 kHz – G	5–10 kHz – Y	5–10 kHz – R	3 kHz – R	25 kHz – Y	25 kHz – Y	25 kHz – Y	≈2 MHz – G	≈8 MHz – G	≈2 MHz – G
Information Service(s)	Facsimile E-mail –Y	Data Voice – B	Data Voice – B	Data – G	Data – G	Data – G	Data Voice – B	Data – G	Data – G	Data – G	Data – G
User Data Rate	600 b/s – R	9.6 or 64 kb/s – G	2.4 or 4.8 kb/s – Y	600 b/s – R	2.4 kb/s (typical) – Y	$\leq$ 31.5 kb/s No system management – G	$\leq$ 19.2 kb/s: Up to 4 TDMA data time slots @ $\leq$ 4.8 kb/s each – G	19.2 kb/s – G	1 Mb/s – B	1 Mb/s – B	1 Mb/s – B
Latency	Includes $\geq$ 250 ms round trip delay – R	Includes $\geq$ 250 ms round trip delay – R	Includes $\geq$ 250 ms round trip delay – R	Includes $\geq$ 250 ms round trip delay – R	Includes media delays – Y	Non-Real Time: Packet overlaps – Y	Near-Real Time: $\leq$ 1s end-to-end for 90+ % – G	– G	– G	– G	– G
System Availability Schedule	Available – B	Available – B	Available – B	Available – B	2000 + – G	2000 + – G	2007 + – R	2003 + – Y	2003 + – Y	2003 + – Y	Available – B
Airborne Terminal Costs (B-kit)	Low – G	High – R	Medium – Y	Medium – Y	Low – G	Medium – Y	Medium – Y	Medium – Y	Low – G	High (if no Mode S already) – R	High (if no Mode S already) – R
Airborne Terminal Costs (A-kit)	Low – G	High – R	Medium – Y	Medium – Y	Low – G	Medium – Y	Medium – Y	Medium – Y	Medium – Y	Medium – Y	Medium – Y
Service Provider and/or Other Costs	Medium – Y	Medium – Y	Medium – Y	Medium – Y	Medium – Y	Medium – Y	Low – G	Low – G	Low – G	Low – G	Low – G

Relative Qualitative Definitions:

Color	Description for Intended Application
Blue (– B)	Exemplary; Needed; Inexpensive; etc.
Green (– G)	Good; Desirable; Affordable; etc.
Yellow (– Y)	Satisfactory; Possibly; “Pricey”; etc.
Red (– R)	Deficient; Undesired; Expensive; etc.